ULTRASONOGRAPHY

Obstetric ultrasound: where are we and where are we going?

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REVIEW ARTICLE

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Diagnostic ultrasound (DUS) is, arguably, the most common technique used in obstetrical practice. From A mode, first described by Ian Donald for gynecology in the late 1950s, to B mode in the 1970s, real-time and gray-scale in the early 1980s, Doppler a little later, sophisticated color Doppler in the 1990s and three dimensional/four-dimensional ultrasound in the 2000s, DUS has not ceased to be closely associated with the practice of obstetrics. The latest innovation is the use of artificial intelligence which will, undoubtedly, take an increasing role in all aspects of our lives, including medicine and, specifically, obstetric ultrasound. In addition, in the future, new visualization methods may be developed, training methods expanded, and workflow and ergonomics improved.

Keywords: Artificial intelligence; Doppler, 3-D, 4-D; Obstetrics, training, ultrasound

Introduction: from "Snowstorm" to Life-like Images

The initial use of ultrasound in medicine was for therapeutic applications rather than diagnosis. The effect was obtained by heating and disrupting tissues (This is fascinating when one considers that bioeffects of diagnostic ultrasound are based on two mechanisms: thermal and non-thermal or mechanical and that modern ultrasound machines display two on-screen indices, related to these effects: the thermal index [TI] and the mechanical index [MI]. See paragraph on Safety, below). This was based on laboratory work performed in the 1920s by the French physicist Paul Langevin who observed fish dying when in the ultrasonic beam [1], as later confirmed Harvey and Loomis [2]. Only later was ultrasound found to permit "visualizing" internal anatomy [3]. Therapeutic usage was found in various branches of medicine, including gynecology, for instance for the treatment of urinary incontinence or ovarian disorders [4]. The beginnings of the remarkable history of diagnostic ultrasound (DUS) in Obstetrics and Gynecology (Ob/Gyn) really started in June 1958 with Professor Ian Donald's Lancet paper on diagnosis of ovarian cyst with a technology newly applied to medicine: ultrasound [5]. This publication also contains the first ultrasound images of a fetal head, although someone trained today would find it very difficult to distinguish any anatomical landmarks in this picture made of black and white dots (Fig. 1, not from Ian Donald's publication). They are a world away from images that can be obtained with modern machines (Fig. 2). It is noteworthy that one year later, in 1959, the first National Ultrasound Conference was convened in Wuhan, China, while the First International Conference on Diagnostic Ultrasound was held in Pittsburgh, in 1965 and the First

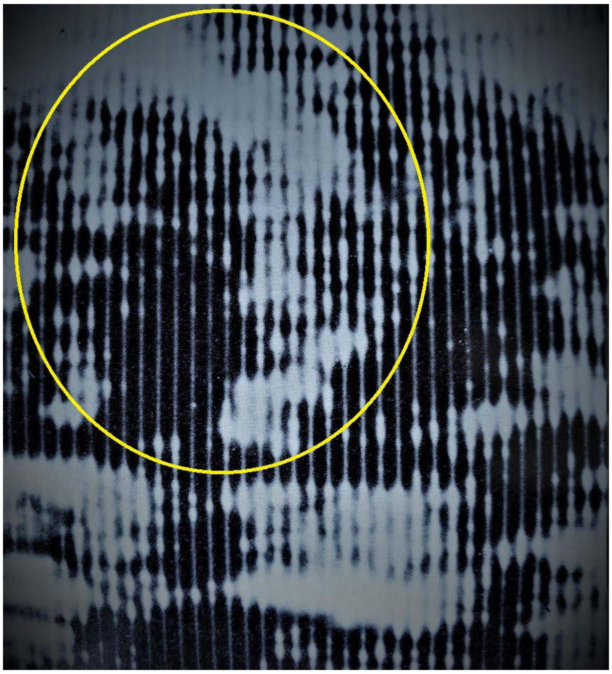


Fig. 1. **B-scan image of the fetus (circa 1980).** The white "smudge" in the center of the picture is the fetal head (within the yellow circle).

Fig. 2. **3D reconstruction of fetal face.** Facial features are very clear in this surface reconstruction.

World Congress on Ultrasonic Diagnostics in Medicine in Vienna, in 1969. Those interested in historical details may refer to Professor Seung's description of the World Federation for Ultrasound in Medicine and Biology (WFUMB) history and the history of ultrasound on the WFUMB website (https://wfumb.info/pdfhistory-2/).

The Past (But Still Current)

Ultrasound, at first, a series of green spikes on a screen (amplitude- or A-mode) became white dots (brightness- or B-mode), first described in Ob/Gyn by Donald et al. [5]. The concept of real-time ultrasound, as opposed to static scan being able to follow movements was introduced in 1968 [6] and was quickly followed by gray-scale. While many scientists were involved in the early steps of ultrasound, several Japanese researchers in the late 1950s–early 1960s were among the prominent investigators of the new technology, such as Kenji Tanaka, Toshio Wagai, Hisaya Takeushi, and Kazuo Maeda, among many others. Fetal biometry was born when Stuart Campbell published the first description of measurements of the fetal biparietal diameter (BPD) in 1968 [7]. Naturally, B-mode, gray-scale, real-time ultrasound still forms the basis of how we practice nowadays.

Indications for the use of DUS in Ob/Gyn expanded as more and more research in the field with this "amazing new technology" was published. One major advance was the introduction of transvaginal ultrasound. The first transvaginal transducer, placed like a ring on a gloved finger and generating A-mode images, was produced in Japan, in 1955 by Aloka. Interestingly, therapeutic use of endovaginal vaginal ultrasound was described a year later [8]. In fact, as previously stated, ultrasound was used as a therapeutic procedure for many years [9], before it became a diagnostic instrument [10]. Models of vaginal transducers more similar to those in use today were produced later and first used in reproductive medicine [11] and, only a little later in obstetrics. They allowed earlier pregnancy assessment with improved visualization due to the use of higher transducer frequencies [12], screening for fetal anomalies, using uterine artery Doppler to predict pre-eclampsia and preterm birth, as well as detection of ectopic pregnancy or pregnancy of unknown location, evaluation of pelvic masses and screening for ovarian cancer and, naturally, use in reproductive medicine.

These "technological innovations" form the base of "modern" DUS in Ob/Gyn as most are still in use today, albeit, possibly, greatly improved over time.

The Present (State of the Art)

The indications for DUS in Ob/Gyn today are quite extensive [13,14]. Various scientific societies have published guidelines on these topics, for instance on the practice of ultrasound in the 2nd and 3rd trimesters [15,16].

One cannot conceive of practicing Ob/Gyn today without access to ultrasound. There have been several improvements in ultrasound technology in recent years, such as harmonic imaging, high-contrast resolution, speckle reduction, one-touch image optimization and increased automation. These are all technical well accepted means to improve the images with no specific obstetric implications and only harmonic imaging will briefly be considered here. Additional developments have become part of the daily armamentarium. Examples include Doppler ultrasound, matrix probe and, naturally, three–four-dimensional ultrasound. These and other advancements have allowed moving back DUS fetal anatomy survey and fetal anomalies diagnosis from the traditional second trimester (18–20 weeks) to the end of the first trimester. Other aspects of ultrasound have also become prominent: ergonomics, miniaturization, point of care ultrasound (POCUS), student training and simulation.

Harmonic Imaging

This technique was developed in tandem with the introduction of ultrasound contrast agents (UCA) [17]. It was recognized that ultrasound has some nonlinear properties. Echoes returning from tissues containing UCA are not only at the original fundamental frequency generated by the transducer but at several different frequencies-multiples of the original one, secondary to non-linear or asymmetric vibrations of the UCA. It was quickly realized that the methodology was applicable without the need for UCA. Insonated tissues will vibrate unevenly under the influence of the changing pressures induced by the incident beam, and will, thus, produce echoes at different frequencies, multiple of the original one. Originally considered noise or artifact and was either suppressed or too weak to be measured, these echoes are captured and transformed into meaningful data with increased contrast and improved information. At the beginning, harmonic imaging had to be "turned on" by the examiner. Nowadays, this is the default imaging mode in most ultrasound machine.

Doppler

The Doppler effect is a perceived frequency shift of light and sound waves, named after Christian Andreas Doppler (1803–1853), the Austrian mathematician-physicist-astronomer who postulated that the observed frequency of a wave depends on the relative speed and direction of movement of the source and the observer, thus, erroneously, explaining the changing color of stars (which, in reality is also due to a temperature change). This error was corrected by the French physicist Armand Hippolyte Louis Fizeau (1819–1896) who dealt specifically with light waves (The Doppler effect is known in French literature as the Doppler-Fizeau effect). Fizeau was the first to predict blue and red shifts of light waves. In 1957 Shigeo Satomura, a Japanese physicist, and his team described how the Doppler effect can be used to record heart and peripheral vessels pulsations [18]. This was the first medical application of the Doppler effect. The first description of umbilical cord blood flow with Doppler, by Ashitaka, Murachi and Takemura, as reported by Nimura [19] was in 1968. This was several tears before the "first" reported use of Doppler techniques to study blood velocimetry waveforms in the umbilical arteries by FitzGerald and Drumm, in 1977 [20]. One of the first clinical applications was to study flow in the umbilical cord in high-risk pregnancies, still used extensively in daily clinical practice. The specific umbilical artery Doppler findings correlated with morbidity and mortality in the fetus are absent and, worse, reversed end-diastolic velocity [14,21]. Over the years, the techniques and applications of Doppler in obstetrics have expanded exponentially to include other fetal vessels, the fetal heart and other organs as well as maternal vessels, such as the uterine artery. The middle cerebral artery (MCA) can be useful in two specific medical conditions: fetal growth restriction and fetal anemia. Blood flow to the fetal brain is increased in both these conditions. In growth restricted fetuses, this increase in blood flow is known as the "brain sparing effect" and can be ascertained by measuring the pulsatility index in the MCA [22]. In fetal anemia, such as secondary to Rh sensitization, the peak systolic velocity (PSV) increases in the MCA [23]. A PSV value greater than 1.5 MOM is associated with significant fetal anemia. Doppler of the ductus venosus (DV) was introduced in 1991–1992 [24]. The DV is a small shunt between the portal and umbilical veins to the inferior vena cava. Under normal conditions, 75% of nutrient-rich umbilical vein blood continue to the liver to reach the heart through hepatic veins while the remaining 25% reach the heart directly through the DV. Increased placental resistance is accompanied by blood flow redistribution to vital organs, brain, heart, adrenal glands with increased cardiac afterload and elevated end-diastolic intracardiac pressures and, later, decrease in contractility and compliance, decreased venous forward flow during atrial systole (a-wave) [25] and decreased pressure gradient across the coronary vascular bed necessary to uphold myocardial perfusion [26]. Myocardial oxygen balance may become critical. All this is reflected in the venous system, primarily the DV (and, even later, in the umbilical vein). This is of particular interest in the growth restricted fetus [27]. Doppler, both color and pulsed are also very important in the study of fetal cardiac function [28,29]. Besides analyzing the fetal circulation, Doppler studies of maternal uterine-arcuate vessels have proven to be valuable in different maternal pathologies [30]. Doppler velocimetry will not diagnose all cases destined to develop complications, but will predict with relatively good sensitivity which of these complicated pregnancies will also have detrimental effects on the fetus [30].

3D/4D

Real-life is three-dimensional and the concept of 3D ultrasound images is not new. Kazunori Baba had a setup for 3D ultrasound in the mid1980s. A position sensor was added to the articulated arm of a static scanner with the linear array probe of a real-time scanner mounted on it [31]. The potential of 3D sonography as a technique for visualization of anatomy quickly became evident [32], specifically for imaging of the fetus [33]. It initially (1992) took 6 hours to create one surface image with an external computer (Abramowicz JS, unpublished data). Today surface rendering of one image takes between 20 and 50 milliseconds depending on the volume. There are several methods to obtain 3D scans: free-hand acquisition using a conventional two-dimensional transducer without position sensing, free-hand acquisition with a conventional 2D ultrasound transducer with position sensing and automated acquisition using dedicated volume probes, the most commonly used method. All methods rely on the acquisition of a series of 2D planes that are reassembled by a computer and displayed as a multiplanar reconstruction or a 3D volume. Hence, since every 3D ultrasound is based on 2D ultrasound, the quality of the results will heavily depend on the quality of the 2D acquisition. In obstetrics, in addition, a most important factor of quality is a good quantity of amniotic fluid surrounding the fetus. The use of 3D ultrasound in obstetrics quickly expanded from the original description [34] to multiple indications [35] and sophisticated rendering with standardization of terms [36] and instructions on how to obtain diagnostic scans, for instance the fetal skull and face [37]. Visualization of motion in real-time is possible in 3D ultrasound and has been labelled real-time 3D, live 3D, or 4D [38]. This is specifically useful to demonstrate fetal facial expressions (Fig. 3, Video clip 1), limb position and malformations and for investigation of the heart [39,40]. The actual clinical value of 3D–4D US is difficult to demonstrate but is certainly important for fetal anomalies [41], specifically the fetal brain and heart evaluation [42]. In gynecology, performing an ultrasound exam without coronal views can be considered malpractice but in obstetrics there are still no studies comparing 2D and 3D US in centers where practitioners are not 3D experts and thus, the *routine* use is still debated [43].

Early Anatomy

The newer technologies have expanded the use of DUS in obstetrics to earlier assessment of fetal anatomy [44] and fetal malformations [45], as well as functional analysis of the materno-placental-fetal unit [46]. The appeal of diagnosing fetal anomalies as early as possible in the pregnancy is evident, since it offers more options to the parents and the medical staff (Fig. 4). This notion is not new and predates the "new" technologies as described in the literature originating, as early as 1989, in big part, from Israel [47]. The term "sonoembryology" was introduced by Timor-Tritsch et al. in 1990 [48] and the notion was later enhanced by 3D ultrasound [49]. The concept has long been accepted in most countries [50,51] and is now routinely practiced except, despite serious attempts, in the United States [52] where it is still sporadic but has greatly improved! Two areas where tremendous progress has been made are the fetal brain [53,54] and heart [55]. Although, in many places, fetal cardiac anatomy and function continues to be evaluated at 18–22 weeks, some practitioners have moved it to the late first trimester [56,57], particularly with the use of Doppler and 3D techniques [58], but most of these will still perform a control study at the traditional time.

But the new technologies have also given birth (so to say) to a not-so-desired side enterprise: fetal imaging for souvenir ultrasound, also called keepsake ultrasound, with no medical indication [59]. Many private entities offer to expectant parents the possibility of obtaining 3D images of their unborn baby (for a cost, naturally). This activity is not approved by scientific societies or legal bodies [60].

Safety

With the introduction of new technologies and the ever more extensive application of ultrasound to the early fetus, the issue of safety needs to be briefly addressed [61]. Ultrasound is a waveform with positive and negative pressures and two potential effects in tissues the beam traverses (bioeffects): thermal, indirect effect, secondary to transformation of acoustic energy into heat and non-thermal, or mechanical, a direct effect, as a result of alternating positive and negative pressure. Two on-screen indices indicate the risk of these two effects: the TI indicating the potential for a temperature increase and the MI indicating the risk of cavitation, if gas bubbles are present in the beam of the ultrasound, which is not the case in a human fetus [62]. There are three thermal indices: TIS, for soft tissue, when bone is not present in the beam pathway, as occurs in the first trimester, TIB, for bone when bone is present, as in the second and third trimester and TIC for transcranial scanning, mostly in neonates and adults. Unfortunately, many ultrasound end-users are not knowledgeable about ultrasound bioeffects and safety of ultrasound, nor about safety indices [63]. The first trimester being a time when the fetus is most susceptible to extrinsic insults, it is important to make sure certain rules are followed [64,65], particularly when using Doppler [66]. A temperature elevation less than 1.5°C does most likely not present a bioeffects risk to the embryo/fetus. A temperature elevation >4°C for 5 minutes can present a risk to the embryo/fetus. Doppler, pulsed/spectral in particular, has the potential to reach these levels. The on-screen TI can thus be used by the sonographers and the physicians as a guide regarding the potential for the temperature increase [67]. As a very

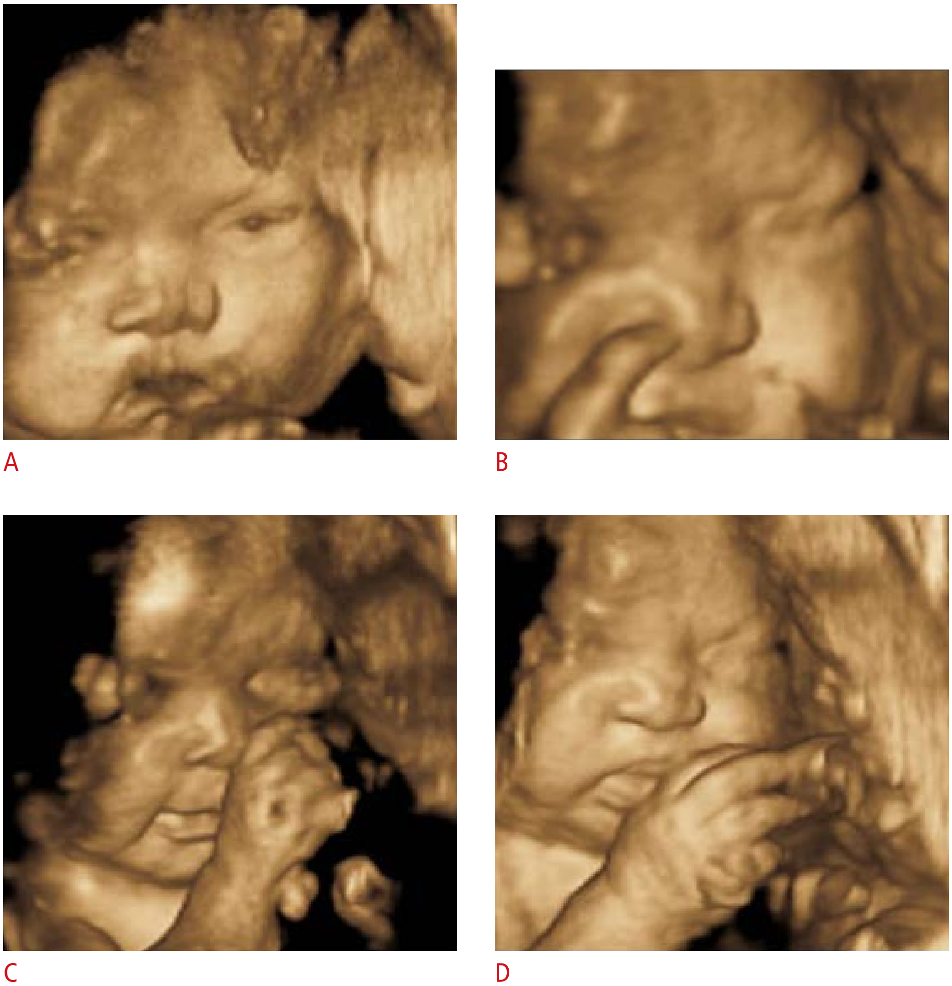


Fig. 3. **Composite picture of various fetal expressions.** These are various expressions: open eyes (A), nose scratching (B), smile (C), and "disgust" (D).

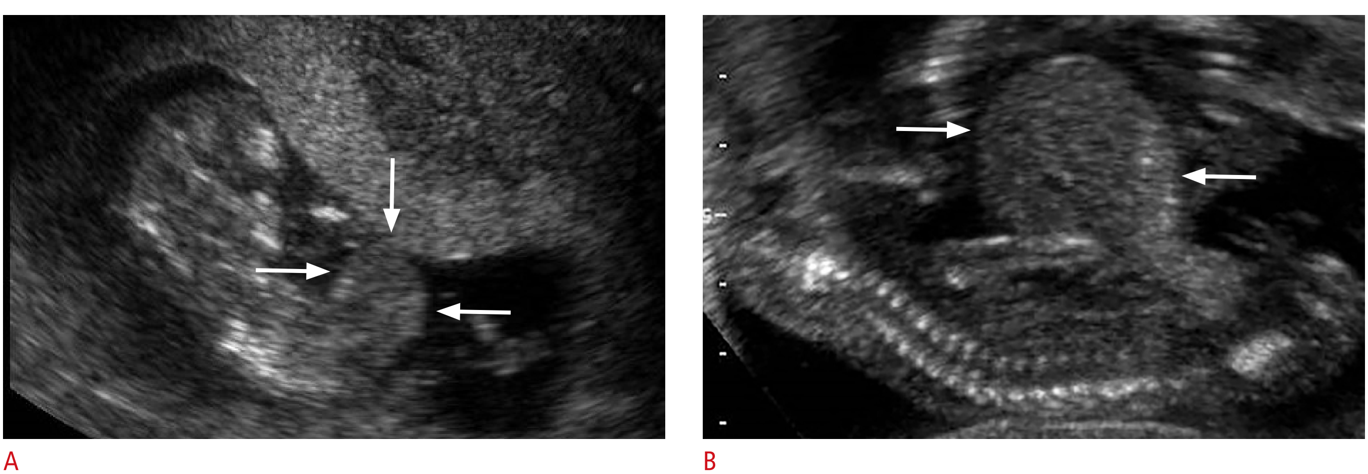


Fig. 4. **Omphalocele at 12 weeks gestational age in a fetus with trisomy 13 (A) and 20 weeks gestational age (B).**
In both images the fetus on his/her back with the head on left and the fetal spine oriented longitudinally on the bottom of the images. Omphalocele is the bulge on the right side of each image indicated by arrows.

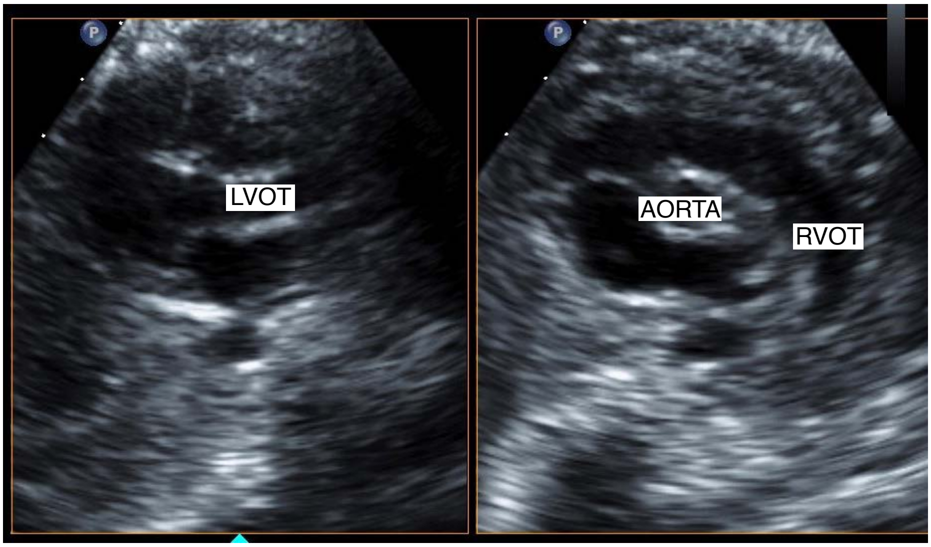


Fig. 5. **Use of matrix probe.** Image of the left ventricular outflow (LVOT) on the left and the right ventricular outflow (RVOT) or short axis on the right are obtained simultaneously. Cross section of the LVOT/aorta is seen on the right since this is a perpendicular view to the RVOT view.

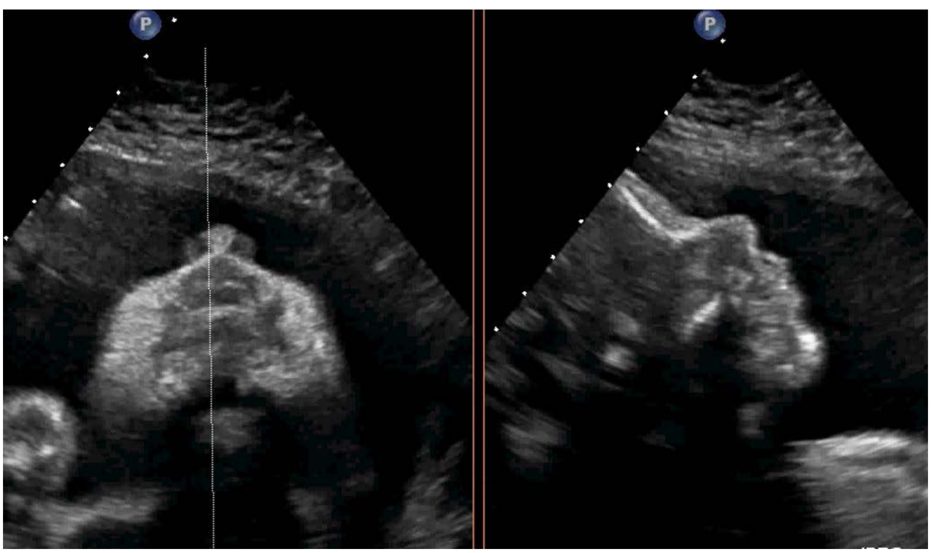


Fig. 6. **Matrix probe image.** Simultaneous viewing of the fetal face in coronal view, face up on the left and the fetal profile on the right.

general rule (not entirely consistent with scientific data but easy to remember), keeping both TI and MI below 1 is, as far as is known, safe for the fetus, if kept within reasonable, accepted exam length of time, that is, practically, in the vast majority of clinical cases, less than 1 hour [67].

Matrix Probes

The concept of a matrix probe is simple. Rather than a single row of crystals, as is usually the case, matrix probes contain multiple rows with very large number of crystals electronically fired. For instance, the X6-1 XMatrix probe by Philips contains 9,212 elements and their XL14-3 vascular probe, 56,000 elements. The use of a matrix probe eliminates the need to rotate the transducer to obtain orthogonal images. Two planes with identical resolution are obtained simultaneously. Images are displayed using a split-screen format (Figs. 5, 6). For instance, the left side will show a longitudinal section of the fetal spine while the right side shows one of several possible transverse planes of that spine. Planes can be changed by electronically steering the ultrasound beam in lateral, rotation or elevation planes. A matrix probe allows real-time multiplanar rendering as well as 3D and 4D [68]. This saves time and decreases wrist strain (see next paragraph).

Ergonomics

Work related musculoskeletal disorders (WRMSDs) are painful chronic injuries affecting the muscles, nerves, ligaments, and tendons of up to 90% of sonographers [69] as well as a large, but undocumented, number of physicians and other users of DUS.

Twenty percent of symptomatic sonographers suffer career-ending injuries [70]. They are due to repeated injuries, secondary mostly to bad work posture and poorly designed examination rooms, exam room chairs and tables and ultrasound transducers and instruments. They mostly affect the neck (58% vs. 25% in controls), shoulder (51% vs. 11%), lower back (44% vs. 26%), and hand (42% vs. 9%) [71]. It is only relatively recently that the concern about WRMSDs has been raised [72]. Recommendations for improvements have been published and progress has been made for instance in monitor design, making them height adjustable with swivel and tilt capability and even mounted on articulated arms (Fig. 7) as well as in transducer technology and one manufacturer has "broken" the ultrasound machine and separated the transducers from the main unit and connected them to lighter weight cables, in addition to suspending them on a retractable cable (Fig. 8).

Fig. 7. **Monitor on articulated arm.** This allows the monitor to be moved in all directions to allow easier visualization for the patient and the clinician.

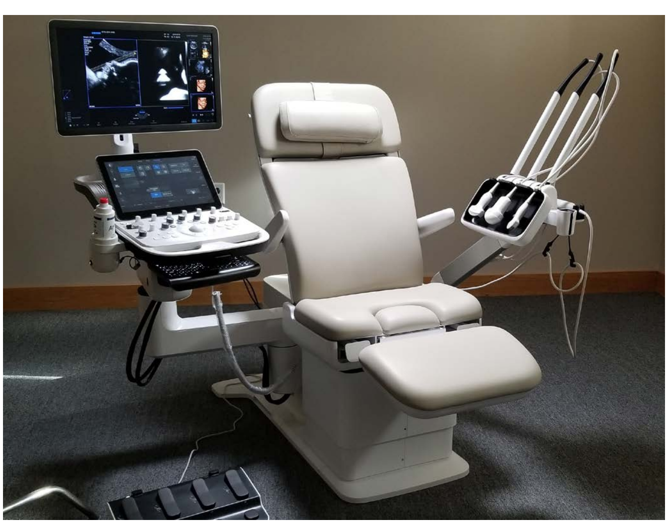


Fig. 8. **"Deconstructed" and "reconstructed" ultrasound system.** This is an example of a "revolutionary" concept of separating various elements of the ultrasound system. The probes are on one side (right) of the examination chair with a probe holder with recoiling cables while the monitor and keyboard are on the other side (left) of the chair and the actual CPU under the chair.

Ultrasound Contrast Agents

All ultrasonographic images depend on echoes being returned from insonated structures (acoustic backscatter). Therefore, increasing the amount of an echo-producing substance in the insonated area will create additional echoes and thus, if properly processed, will provide additional information [73]. This may allow, for instance, to analyze perfusion or absence thereof or changes in vascular patterns in tiny vessels, beyond the resolution of gray scale ultrasound ultrasonography, color or power Doppler imaging, such as placental vasculature [74]. The use of contrast enhanced ultrasound (CEUS) in obstetrics is extremely limited and has not really changed over the years [75]. Placental vascularity and its alterations may clearly be demonstrated with CEUS [76]. Reports of the use of CEUS in obstetrics include demonstration of abnormally located trophoblastic blood flow in thirty-three ectopic pregnancies [77], two cases of placenta accrete [78], and a report on fourteen cases of complicated monochorionic twin pregnancies with injection of the contrast agent into the intrahepatic umbilical vein of one twin to evaluate twin-twin transfusion and delineate placental vasculature [79]. All these reports were related to analysis of placental flow which was and remains the only indication for the use of CEUS in obstetrics, since safety of these agents for the fetus has not been ascertained. Their value is clearer in gynecology and has been demonstrated, specifically, for the differentiation between benign and malignant ovarian tumors [80].

Fig. 9. **Crystal view of the fetal spine (used with permission of Samsung Healthcare).** This is one of the new advanced 3D volume post-rendering technology.

Additional Technologies

There are also new ultrasound imaging modalities introduced by several ultrasound manufacturer, based on computer manipulation of the echoes, such as Samsung's crystal view (Fig. 9) or GE's HD*live* Silhouette (Fig. 10). Some of the technology combines positions and gradients of intensity to enhance visualization of both internal and external structures in a single rendered image providing 3D-like visualization of flow in blood vessels and clearly revealing vessel boundaries: MicroFlow Imaging (Philips), MV-Flow and LumiFlow (Samsung) (Fig. 11), Radiant*flow* (GE), Slow*flow*HD (GE) (Video clips 2, 3) as well as new smart imaging algorithms for analysis of fetal anatomy, such as the brain and heart (see paragraph on artificial intelligence [AI]) or heart function, e.g., *fetal*HQ (GE) where the software uses speckle tracking to analyze the motion of multiple points of the fetal heart to provide information on its size, shape, and function (Fig. 12, used with permission of GE Healthcare) [81], Others include GE's HD*live*, HD*live* Flow, HD*live* Studio, *e*4D, *e*STIC (Video clip 4). While producing beautiful images (Fig. 13), the actual clinical value of these modalities is still being investigated.

Miniaturization

Miniaturization in ultrasound practice has made tremendous strides, from huge static-scan consoles to still large and heavy but movable machines (Fig. 14), to much smaller and movable real-time instruments (Fig. 15), to laptop (Fig. 16), hand-held scanners (Fig. 17), to using a tablet or smart phone as a monitor (Fig. 18). The earliest record of a hand-held instrument appears to date from 1978 [82]. The idea, however, did not catch the attention of ultrasound

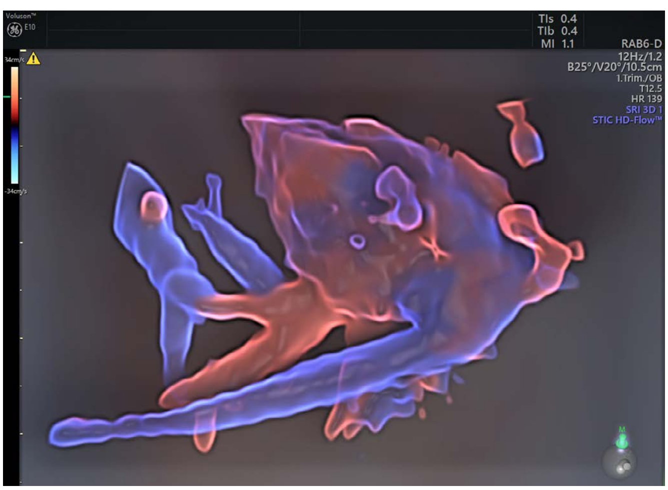


Fig. 10. **HDlive Silhouette of fetal circulation (used with permission of GE Healthcare).** This is a rendering method that produces realistic images by using an advanced illumination model with vitreous-like clarity.

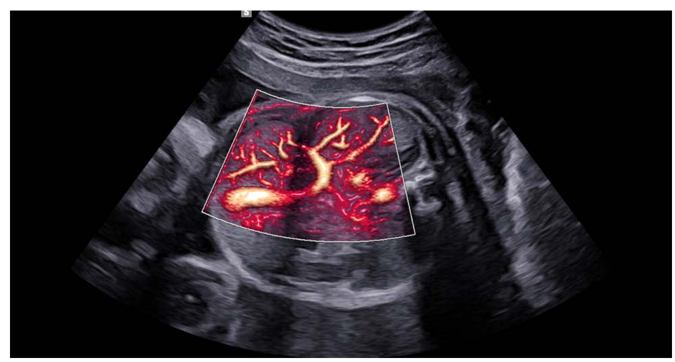


Fig. 11. **Fetal abdomen vasculature, with MV-Flow with Lumi Flow (used with permission of Samsung Healthcare).** MV-Flow, for microvascular, is an advanced Doppler technology that provides detailed documentation of microvascular perfusion into tissues and organs and LumiFlow displays a "3D-like" appearance to 2D color Doppler, enhancing spatial comprehension of blood vessels and aiding in the understanding of vessel boundaries as can be seen in this detailed view of fetal abdominal vasculature.

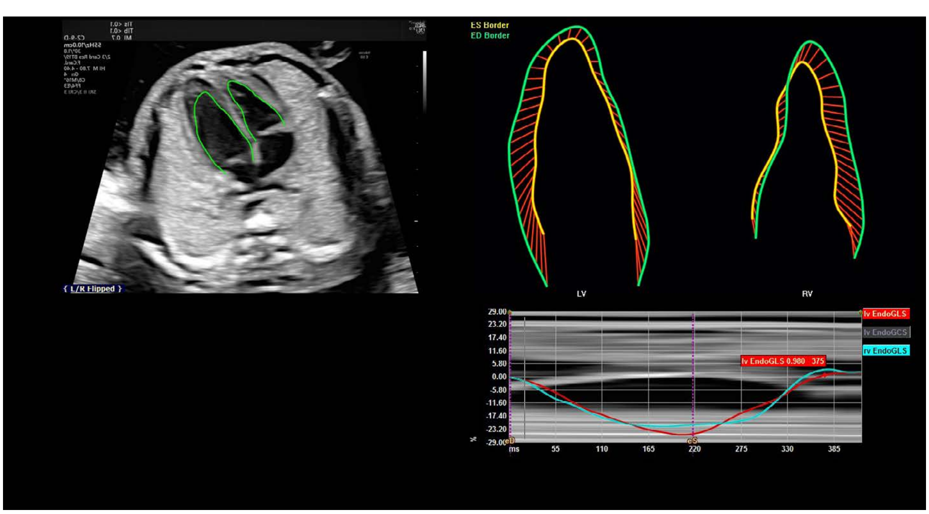


Fig. 12. **Analysis of fetal heart function with Fetal HQ (used with permission of GE Healthcare).** This tool, previously utilized in adults only, allows automatically tracking and measuring strain while performing a fetal echocardiogram by segmenting the heart in many small elements and analyzing directions and intensities of the various movement vectors. This furnishes simultaneous information on the size, shape and function of the fetal heart.

users until much later, mostly because or relatively poor image quality. This has changed recently with a multitude of companies producing ultrasound machines, besides the "big ones" [83]. In 2018, sales of handheld ultrasound accounted for about US $138 million or about 2% of the $6.9 billion global market for ultrasound equipment. By 2023, the global market for handheld ultrasound is forecast to exceed US $400 million [83]. The renewed interest was a result of improvements in the image quality and simplification of use with a minimal number of controls. The majority of users are emergency room physicians, with the development of POCUS but other specialties are increasingly using this modality in office practice.

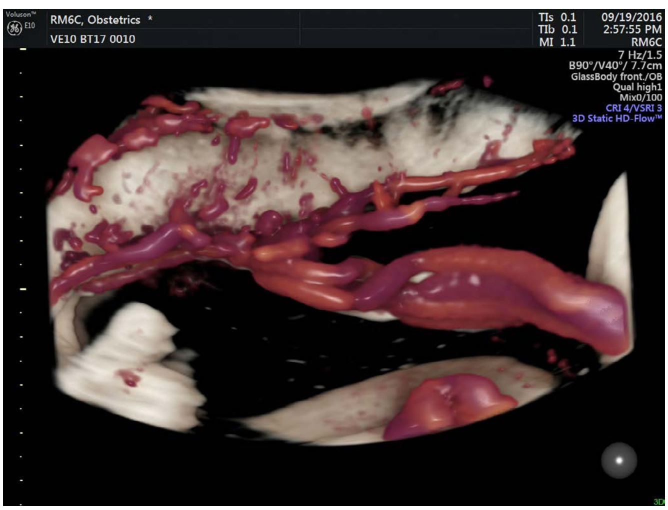


Fig. 13. **Umbilical cord insertion into the placenta and placental surface vessels.** This is imaged with special software (Radiant flow). This gives the impression of a real-life picture.

POCUS

This may be the field with the most recent expansion. The concept behind POCUS is to allow diagnosis at the patient bedside whether at the hospital, in an ambulance, or in the field. It has been shown to help emergency room physicians make fast and accurate decisions without needing to refer the patients to more complex imaging procedures [84], which may be particularly relevant during pandemics, such as the corona virus disease 2019 (COVID-19) [85] although this is not always the case [86]. Because of its ever-

Fig. 14. **"Old" ultrasound system.** Note the massive size, rendering transport relatively difficult and the "old style" monitor that can be only minimally moved.

Fig. 15. **Various "new" portable ultrasound systems (modified from Enterprise Ultrasound, https://enterpriseultrasound.com).** They have common characteristics: much smaller than older systems, LCD monitors than can move virtually in every direction, movable keyboard, often touch screen, larger wheels that allow easy transportation to various parts of the medical facility, and, in general, upgradability.

expanding usage, including, for instance, for the emergency room patient with vaginal bleeding in early pregnancy, safety education of the end-users is particularly important [87]. POCUS is not a replacement for comprehensive ultrasound, but rather an option for physicians to have immediate access to clinical imaging for rapid and direct solutions. In obstetrics, POCUS has penetrated the labor and delivery suite but has also remote areas where imaging was, until now, not available [88].

Student Training

The advent of POCUS has facilitated the introduction of ultrasound education to medical schools [89]. This is expanding and includes virtually all branches of medicine, including obstetrics and gynecology [90]. In addition, simulation (see next paragraph) has (or should) become an integral part of training programs at all levels, in all disciplines.

Fig. 16. **A laptop model of ultrasound system.** Many vendors offer these machines that, with time, have become of excellent quality, albeit, not quite as good as the "stars" from the major vendors.

Simulation

In a review on state-of-the-art ultrasound in obstetrics (or other ultrasound applications), together with comments on student training, some remarks on simulation are in order [91]. Simulation is a training method that enables educators and learners (medical, sonography and other fields students, residents and fellows) to practice ultrasound (diagnostic and therapeutic) without the need to scan real subjects or patients. The advantages of using ultrasound simulation are visualization of large numbers of normal and abnormal cases, e.g., fetal anomalies [92], automatically generated feedback and standardized testing. Simulation should, therefore, be integrated in ultrasound education programs [93]. Several commercial companies offer simulation models or computer-based programs in obstetrics and gynecology.

The Future (It's Almost Here)

Many technologies are available today, some on a research basis, some in more advanced stages, even to the point of already being available but with limited clinical applications as of now. This, of course, changes almost daily, as new research publications appear.

Fig. 17. **Handheld "miniature" system.** This is becoming more and more common because of the ease of transport in the practician's pocket and ease of use.

Fig. 18. **Two systems using smart phones as monitors.** This is a further advancement with the probe attaching directly to a cell phone. One only need to download the application.

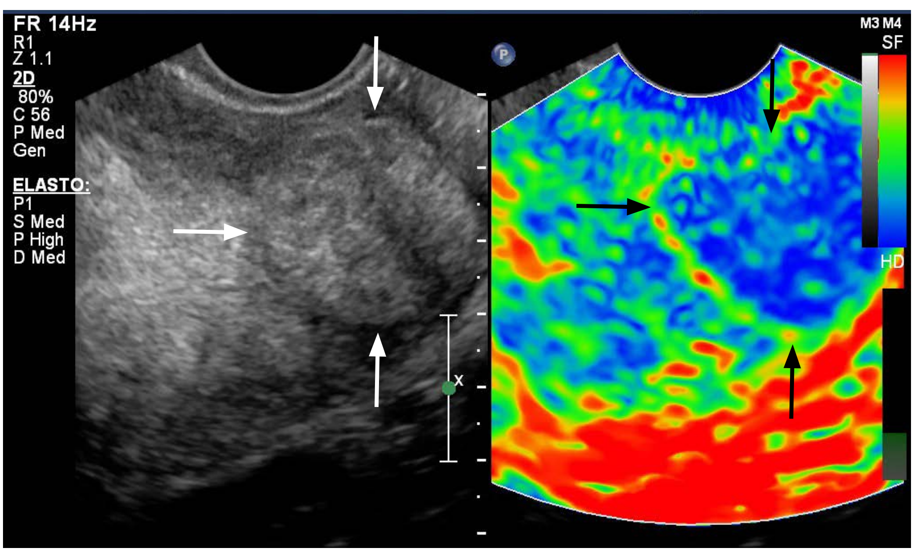
The major ones are elastography (established but for limited applications in obstetrics), teleultrasound (established in certain areas but which will probably expand in the future), AI, super-resolution ultrasound and laser ultrasound.

Elastography

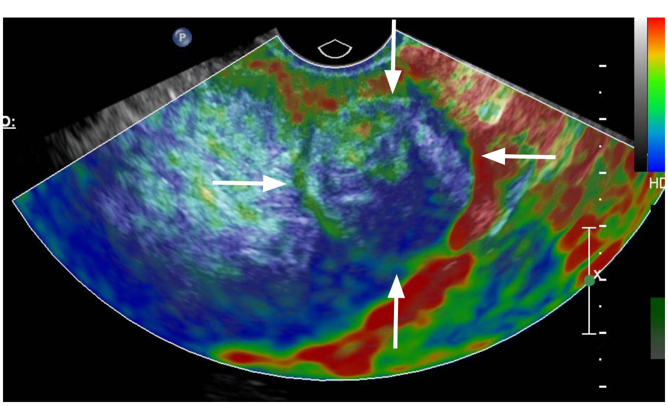
Elastography is a relatively new technique that exploits the fact that tissues have intrinsic elastic properties that can be altered by a pathological process [94]. This change in elasticity is detectable and imaged using elastography (Fig. 19). Two types are recognized: quasi-static or strain elastography, also known as static or compression elastography and shear-wave elastography. In strain elastography a mechanical force is manually applied to cause the displacement of tissues and in shear wave elastography an acoustic force creates a mechanical impulse that induces displacement of tissues in the form of shear-waves [95]. The usefulness in obstetrics has been investigated for the cervix [96], specifically to attempt and predict preterm labor [97], and the placenta [98] and in abnormal placental invasion to differentiate between placenta accreta spectrum (formerly known as morbidly adherent placenta) [99].

Teleultrasound

Ultrasound is an integral part of obstetrical care. However, this modality is not available in remote areas, or, more specifically, the expertise to interpret the images may be lacking locally. Referral to a central center may involve long travel time and large expenses. Teleultrasound is a critical solution [100]. It is possible to train non-experts to obtain images and transmit them to the obstetric or radiology department [88]. The transmission of fetal ultrasound images has long been achieved [101] but several issues remained, image quality being the most important, although excellent diagnostic quality can be obtained [102]. Better quality can be achieved with asynchronous transmission, i.e., transmission, storage and later analysis although real-time transmissions may be



A



B

Fig. 19. **Elastography of a myomatous uterus.**
A. On the left panel, the regular 2D gray-scale image, the myoma is visible as the round structure on the right (arrows). The myoma is visible with elastography on the right panel, as it appears surrounded by a layer of tissue (arrows) with different elasticity ("capsule"). B. A different elastography color scheme is used which optimally demonstrates the myoma (arrows).

preferred because of instantaneous feedback to the operator and immediate diagnosis and clinical decision. Cost is, generally, much higher for real-time transmission. This will, naturally, become less of an issue in the future with newer transmission technologies. The use of teleultrasound has been demonstrated to be of value in obstetrics to confirm pregnancy, monitor fetal growth, and evaluate certain pregnancy-related complications such as malpresentation, placenta previa or placenta accreta [103]. Wireless transducers have been introduced and may become a major part of this effort as teleultrasound is well accepted by users and patients [104]. The 2019–2020 severe acute respiratory syndrome coronavirus 2 pandemic (COVID-19) has certainly made telemedicine and teleultrasound a major component of medicine of today, not tomorrow.

Artificial Intelligence

While it is well beyond the scope of this article to go into details regarding this huge and burgeoning branch of science, a few principles will be described. In medicine, the idea is that tremendous amounts of information ("big data") together with machine learning can create algorithms that perform as well as, if not better than, and much faster than human physicians [105]. The inspiration is the human brain, hence the designation artificial neuronal networks and machine learning, where the computer automatically recognizes patterns, based on entry of enormous quantities information bits, such as "ideal" ultrasound images of the fetal anatomy. The computer can then perform automatic measurements, for example fetal biometry [106]. In machines from several manufacturers, automatic image recognition is already being used to perform measurement of the fetal BPD, head circumference (HC), abdominal circumference, and femur length. As example, with automatic evaluation, after deep learning, a success rate of 91.43% and 100% for HC and BPD estimations were obtained, respectively, with an accuracy of 87.14% for the plane acceptance check [106]. In another study of automatic measurement of the HC, the average measurement error was 1.7 mm, better than measurements with

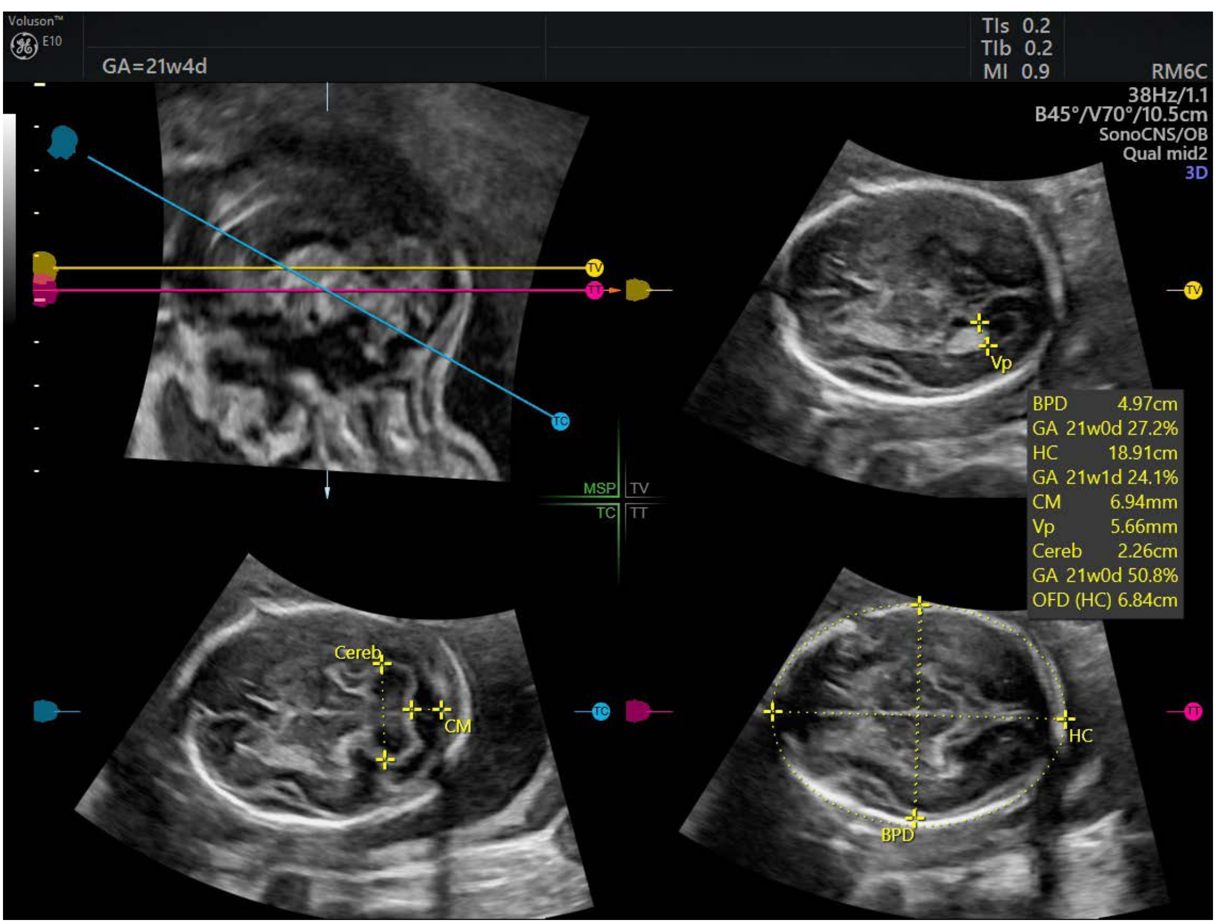


Fig. 20. **Automatic display of fetal brain planes (used with permission of GE Healthcare).** This was obtained after a single sweep. Measurements of the biparietal diameter (BPD), head circumference (HC), cerebellum, cisterna magna (CM), and posterior horn of the lateral ventricle (Vp) are automatic. GA, gestational age; OFD, occipitofrontal diameter.

traditional methods [107]. Some machines will give feedback to the examiner on whether he/she has obtained the correct image and how to correctly position the transducer to obtain these images. AI will play an increasingly important role in image interpretation, such as whether the anatomy displayed is normal or not. When AI solutions are adapted to handheld ultrasound instruments, one can expect the less expert examiners detect anomalies of growth, morphology, or function. Two good examples are the fetal brain and heart. The large amount of data stored in the machine allows for very fast analysis of what the examiner acquires with one 3D sweep and quick display of multiple planes (axial, sagittal and the almost never attainable coronal, allowing diagnosing anomalies of the

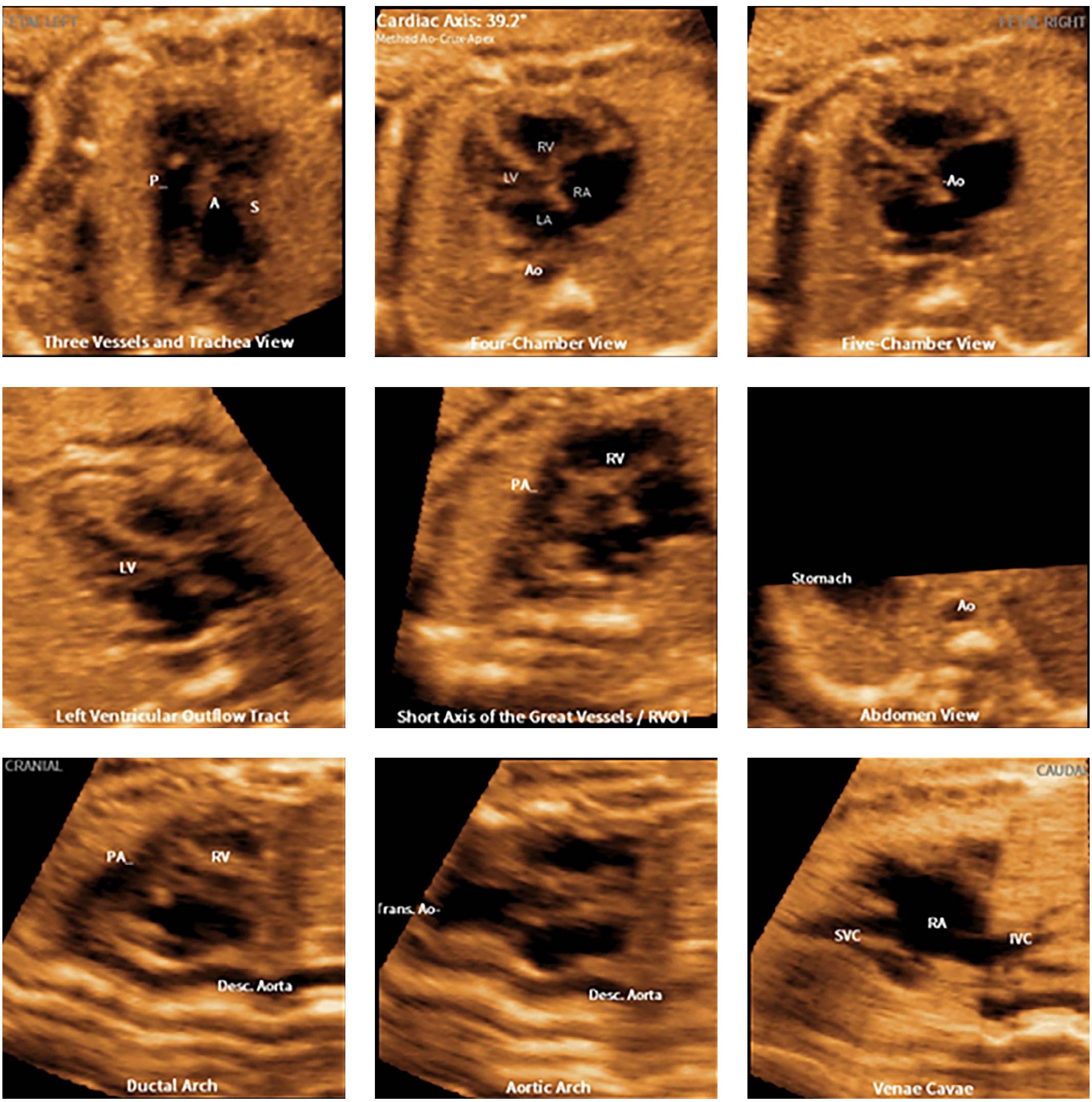


Fig. 21. **Nine views of the fetal heart (used with permission of Samsung Healthcare).** These are displayed automatically after a single sweep. Labels are added automatically by the machine and move with the structures, for instance if zoom is applied.

midline and posterior fossa which cannot, generally, be visualized on the axial planes) as well as measurements of the various fetal brain structures (SonoCNS Fetal Brain, developed by GE Healthcare [Fig. 20, used with permission] and 5D CNS+ by Samsung). For instance, in 98.3% (118/120), 5D CNS successfully reconstructed the axial diagnostic planes and calculated all the basic biometric head and brain measurements [108]. In addition, workflow efficiency is improved, wrist fatigue is reduced and inter-observer variability is lessened [109]. Similarly automatic display of fetal heart views is possible, for instance GE's SonoVCAD heart, Samsung's 5D heart (Fig. 21) or Canon's SmartFetalHeart, even with annotation of the various parts, after a single sweep [110]. Similarly some tools allow fully automatic and accurate acquisition of the most significant planes of the entire fetal anatomy and frequently used measurements of fetal biometry which can be displayed after a single sweep (Sonoscape's S-Fetus). One of the biggest players on the AI block is the UK-based company Intelligent Ultrasound, which acquired over 1 million high-quality images from real obstetric scans to develop algorithms for the software ScanNav. The idea is to provide guidance, in real-time, to the ultrasound user by automatically capturing the correct images. Audit and, thus, quality improvement are possible.

Super-resolution Ultrasound

Ultrasound imaging is limited in resolution by the wavelength (in general resolution=1/2 wavelength), which depends on the frequency (wavelength=speed of sound/frequency), hence higher frequencies transducers, having smaller wavelength allow for improved resolution. Echoes returning from scanned structures depend on the concentration of scatterers in the tissue, i.e., structures that are "hit" by the ultrasound beam. It is, therefore, difficult to image small blood vessels, because of limited number of slowly (<1 cm/s) moving scatterers. Adding contrast agents (microbubbles) may improve the visualization (see above) but also has limits. Super-resolution ultrasound imaging is a new technique which allows, after introducing a microbubbles visualization of microvascularity at a resolution of tens of microns [111,112]. A major advantage over classic high-frequency techniques, where higher frequency means lower penetration, is that with super-resolution ultrasound there is no penetration trade-off associated with higher frequencies [111]. This may allow in the future precise mapping of placental vasculature or fetal brain, for instance in early stages of fetal growth restriction.

Laser Ultrasound

Conventional ultrasound imaging requires the placement of a transducer in contact with the patient to transmit a beam and receive returning echoes. Laser ultrasound operates analogously to conventional ultrasound but uses light instead of piezoelectric elements with no need to actually have close contact with the patient [113]. One laser remotely generates, by heat transfer, sound waves that bounce through the body. A second laser remotely detects the reflected waves, which are then translated into an image similar to conventional ultrasound. Human imaging has been obtained [113], although the technology is still at the research stage.

Who Is Paying for All This?

In a world of managed care or limited resources, economics is key. Several inevitable questions arise: Who pays for routine scans with conventional ultrasound, and who pays for the advanced modalities? Will these new technologies allow more patients to be seen, faster, and at a lower cost? Will we be able to reach farther to less favored regions of the globe? Will we shorten hospital stay? Administrators will ask for a justification to purchase a new machine or one with more bells and whistles by demonstrating increased productivity and, unfortunately, not necessarily by better care-giving, assuming the new technologies improve diagnostic capabilities by better imaging, objective assessment and, possibly, shorter exam time, which translates in more patients being seen. Ultrasound continues to be the cheapest imaging modality after plain X-rays, much cheaper than computed tomography or magnetic resonance to buy, operate, and maintain.

Conclusion

Ultrasound in Ob/Gyn is alive and well. It has, perhaps, become the most ubiquitous procedure in daily clinical practice. While this article describes some of the technologies that were introduced over the years and discusses some newer ones already functional and some on the verge of becoming routine, many more may appear as the power of computers and other electronic expertise continue to expand. Based on scientific advances, past, present and future, ultrasound appears to have a long life ahead of it.

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Conflict of Interest

I am on the advisory board of Samsung and an author for UpToDate.

Supplementary Material

Video clip 1. Yawning (Clip courtesy of GE Healthcare). In this clip, the fetus is seen opening and closing his/her mouth (yawning) (https://doi.org/10.14366/usg.20088.v001).

Video clip 2. Fetal brain vasculature, with SlowFlow HD Flow (used with permission of GE Healthcare). This allows visualizing blood perfusion in very small vessels with low velocities, such as the fetal brain, as demonstrated in the clip. This also uses RadiantFlowHD (see below, Video clip 3) (https://doi.org/10.14366/usg.20088.v002).

Video clip 3. Fetal circulation with RadiantFlow HD Flow (used with permission of GE Healthcare). This is a technique whereby 2D color Doppler images are transformed into what appears to be 3D images, allowing for clearer visualization of the vessels (https://doi.org/10.14366/usg.20088.v003).

Video clip 4. Fetal heart image with TUI eSTIC (used with permission of GE Healthcare). This is a spatio-temporal image correlation (STIC) technique where successive sections of the STIC acquisition are displayed separately but simultaneously on screen. A ventricular septal defect is clearly visible in the middle of the ventricular septum (https://doi.org/10.14366/usg.20088.v004).

References

1. Langevin P. Les ondes ultrasonores. Rev Gen Electr 1928;23:626-634.
2. Harvey EN, Loomis AL. The destruction of luminous bacteria by high frequency sound waves. J Bacteriol 1929;17:373-376.
3. Gohe H, Wedekind T. Der Ultraschall in der Medizin. Klin Wochenschr 1940;19:25-29.
4. Aroso A, Ferreira E. Ultrasonic therapy in microcystic disease of the ovary. C R Soc Fr Gyncol 1951;21:351-353.
5. Donald I, Macvicar J, Brown TG. Investigation of abdominal masses by pulsed ultrasound. Lancet 1958;1:1188-1195.
6. Hofmann D, Hollander HJ. Intrauterine diagnosis of hydrops fetus universalis using ultrasound. Zentralbl Gynakol 1968;90:667-669.
7. Campbell S. An improved method of fetal cephalometry by ultrasound. J Obstet Gynaecol Br Commonw 1968;75:568-576.
8. Baccaglini M. Results of endovaginal ultrasonic therapy in gynecology. Minerva Fisioter Radiobiol 1956;1:39-40.
9. Kos M, Najmr Z, Kubicka J. Ultrasonic therapy of gynecological diseases. Cesk Gynekol 1952;17:627-634.
10. Taylor ES, Holmes JH, Thompson HE, Gottesfeld KR. Ultrasound diagnostic techniques in obstetrics and gynecology. Am J Obstet Gynecol 1964;90:655-671.
11. Bernaschek G. Advantages of endosonographic diagnosis in gynecology and obstetrics. Geburtshilfe Frauenheilkd 1987;47:471-476.
12. Timor-Tritsch IE, Farine D, Rosen MG. A close look at early embryonic development with the high-frequency transvaginal transducer. Am J Obstet Gynecol 1988;159:676-681.
13. Abramowicz JS. Benefits and risks of ultrasound in pregnancy. Semin Perinatol 2013;37:295-300.
14. Shipp TD. Overview of ultrasound examination in obstetrics and gynecology [Internet]. Waltham, MA: UpToDate, 2020 [cited 2020 May 26]. Available from: https://www.uptodate.com/contents/overview-of-ultrasound-examination-in-obstetrics-and-gynecology.
15. ISUOG Education Committee recommendations for basic training in obstetric and gynecological ultrasound. Ultrasound Obstet Gynecol 2014;43:113-116.
16. AIUM practice parameter for the performance of detailed second- and third-trimester diagnostic obstetric ultrasound examinations. J Ultrasound Med 2019;38:3093-3100.
17. Burns PN, Powers JE, Fritzsch T. Harmonic imaging: a new imaging and Doppler method for contrast-enhanced ultrasound. Radiology 1992;185:142.
18. Satomura S. Ultrasonic Doppler method for the inspection of cardiac function. J Acoust Soc Am 1957;29:1181-1185.
19. Nimura Y. Introduction of the ultrasonic Doppler technique in medicine: a historical perspective. J Med Ultrasound 1998;6:5-13.
20. FitzGerald DE, Drumm JE. Non-invasive measurement of human fetal circulation using ultrasound: a new method. Br Med J 1977;2:1450-1451.
21. Nicolaides KH, Bilardo CM, Soothill PW, Campbell S. Absence of end diastolic frequencies in umbilical artery: a sign of fetal hypoxia and acidosis. BMJ 1988;297:1026-1027.
22. Ozcan T, Sbracia M, d'Ancona RL, Copel JA, Mari G. Arterial and venous Doppler velocimetry in the severely growth-restricted fetus and associations with adverse perinatal outcome. Ultrasound Obstet Gynecol 1998;12:39-44.
23. Mari G, Deter RL, Carpenter RL, Rahman F, Zimmerman R, Moise KJ Jr, et al. Noninvasive diagnosis by Doppler ultrasonography of fetal anemia due to maternal red-cell alloimmunization. Collaborative Group for Doppler Assessment of the Blood Velocity in Anemic Fetuses. N Engl J Med 2000;342:9-14.
24. Huisman TW, Stewart PA, Wladimiroff JW. Doppler assessment of the normal early fetal circulation. Ultrasound Obstet Gynecol 1992;2:300-305.
25. Seravalli V, Miller JL, Block-Abraham D, Baschat AA. Ductus venosus Doppler in the assessment of fetal cardiovascular health: an updated practical approach. Acta Obstet Gynecol Scand 2016;95:635-644.
26. Marsal K. Physiological adaptation of the growth-restricted fetus. Best Pract Res Clin Obstet Gynaecol 2018;49:37-52.
27. Fratelli N, Amighetti S, Bhide A, Fichera A, Khalil A, Papageorghiou AT, et al. Ductus venosus Doppler waveform pattern in fetuses with early growth restriction. Acta Obstet Gynecol Scand 2020;99:608-614.
28. Takano M, Nakata M, Nagasaki S, Ueyama R, Morita M. Assessment of diastolic function of normal fetal heart using dual-

gate Doppler. Ultrasound Obstet Gynecol 2018;52:238-242.
29. Zhang L, Han J, Zhang N, Li Z, Wang J, Xuan Y, et al. Assessment of fetal modified myocardial performance index in early-onset and late-onset fetal growth restriction. Echocardiography 2019;36:1159-1164.
30. Goncalves LF, Abramowicz JS. Uterine artery Doppler. In: Fleischer AC, Abramowicz JS, Goncalves LF, Manning FA, Monteagudo A, Toy EC, et al., eds. Fleischer's sonography in obstetrics and gynecology: textbook and teaching cases. 8th ed. New York: McGraw-Hill, 2018;239-254.
31. Baba K, Satoh K, Sakamoto S, Okai T, Ishii S. Development of an ultrasonic system for three-dimensional reconstruction of the fetus. J Perinat Med 1989;17:19-24.
32. Pretorius DH, Nelson TR, Jaffe JS. 3-dimensional sonographic analysis based on color flow Doppler and gray scale image data: a preliminary report. J Ultrasound Med 1992;11:225-232.
33. Timor-Tritsch IE, Monteagudo A. Three and four-dimensional ultrasound in obstetrics and gynecology. Curr Opin Obstet Gynecol 2007;19:157-175.
34. Merz E, Chaoui R. 30-year anniversary of ultrasound: Clinical use of 3D ultrasound in obstetrics and gynecology (1989-2019). Ultraschall Med 2019;40:288-291.
35. Benacerraf BR, Benson CB, Abuhamad AZ, Copel JA, Abramowicz JS, Devore GR, et al. Three- and 4-dimensional ultrasound in obstetrics and gynecology: proceedings of the American Institute of Ultrasound in Medicine Consensus Conference. J Ultrasound Med 2005;24:1587-1597.
36. Merz E, Benoit B, Blaas HG, Baba K, Kratochwil A, Nelson T, et al. Standardization of three-dimensional images in obstetrics and gynecology: consensus statement. Ultrasound Obstet Gynecol 2007;29:697-703.
37. Tutschek B, Blaas HK, Abramowicz J, Baba K, Deng J, Lee W, et al. Three-dimensional ultrasound imaging of the fetal skull and face. Ultrasound Obstet Gynecol 2017;50:7-16.
38. Campbell S. 4D, or not 4D: that is the question. Ultrasound Obstet Gynecol 2002;19:1-4.
39. Goncalves LF, Lee W, Chaiworapongsa T, Espinoza J, Schoen ML, Falkensammer P, et al. Four-dimensional ultrasonography of the fetal heart with spatiotemporal image correlation. Am J Obstet Gynecol 2003;189:1792-1802.
40. DeVore GR, Polanco B, Sklansky MS, Platt LD. The 'spin' technique: a new method for examination of the fetal outflow tracts using three-dimensional ultrasound. Ultrasound Obstet Gynecol 2004;24:72-82.
41. Merz E, Pashaj S. Advantages of 3D ultrasound in the assessment of fetal abnormalities. J Perinat Med 2017;45:643-650.
42. Chaoui R, Abuhamad A, Martins J, Heling KS. Recent development in three and four dimension fetal echocardiography. Fetal Diagn Ther 2020;47:345-353.
43. Merz E, Abramowicz JS. 3D/4D ultrasound in prenatal diagnosis: is it time for routine use? Clin Obstet Gynecol 2012;55:336-351.
44. Platt LD. Should the first trimester ultrasound include anatomy survey? Semin Perinatol 2013;37:310-322.
45. Pooh RK, Kurjak A. 3D/4D sonography moved prenatal diagnosis of fetal anomalies from the second to the first trimester of pregnancy. J Matern Fetal Neonatal Med 2012;25:433-455.
46. Arakaki T, Hasegawa J, Nakamura M, Takita H, Hamada S, Oba T, et al. First-trimester measurements of the three-dimensional ultrasound placental volume and uterine artery Doppler in early- and late-onset fetal growth restriction. J Matern Fetal Neonatal Med 2020;33:564-569.
47. Rottem S, Bronshtein M, Thaler I, Brandes JM. First trimester transvaginal sonographic diagnosis of fetal anomalies. Lancet 1989;1:444-445.
48. Timor-Tritsch IE, Peisner DB, Raju S. Sonoembryology: an organ-oriented approach using a high-frequency vaginal probe. J Clin Ultrasound 1990;18:286-298.
49. Benoit B, Hafner T, Kurjak A, Kupesic S, Bekavac I, Bozek T. Three-dimensional sonoembryology. J Perinat Med 2002;30:63-73.
50. Salomon LJ, Alfirevic Z, Bilardo CM, Chalouhi GE, Ghi T, Kagan KO, et al. ISUOG practice guidelines: performance of first-trimester fetal ultrasound scan. Ultrasound Obstet Gynecol 2013;41:102-113.
51. Oh SY, Hong JS, Seol HJ, Hwang HS, Park HS, Kim K, et al. 2014 First-trimester ultrasound forum from the Korean Society of Ultrasound in Obstetrics and Gynecology. Obstet Gynecol Sci 2015;58:1-9.
52. Timor-Tritsch IE. Transvaginal sonographic evaluation of fetal anatomy at 14 to 16 weeks. Why is this technique not attractive in the United States? J Ultrasound Med 2001;20:705-709.
53. Altmann R, Schertler C, Scharnreitner I, Arzt W, Dertinger S, Scheier M. Diagnosis of fetal posterior fossa malformations in high-risk pregnancies at 12-14 gestational weeks by transvaginal ultrasound examination. Fetal Diagn Ther 2020;47:182-187.
54. Yang SH, An HS, Lee JS, Kim C. Normal intracranial BS/BSOB ratio values in the first trimester of single gestations with live fetuses in a Korean population. Med Ultrason 2017;19:190-194.
55. McBrien A, Hornberger LK. Early fetal echocardiography. Birth Defects Res 2019;111:370-379.
56. Carvalho JS. Fetal heart scanning in the first trimester. Prenat Diagn 2004;24:1060-1067.
57. Minnella GP, Crupano FM, Syngelaki A, Zidere V, Akolekar R, Nicolaides KH. Diagnosis of major heart defects by routine first-trimester ultrasound examination: association with increased nuchal translucency, tricuspid regurgitation and abnormal flow in ductus venosus. Ultrasound Obstet Gynecol 2020;55:637-644.
58. Yeo L, Romero R. Color and power Doppler combined with Fetal Intelligent Navigation Echocardiography (FINE) to evaluate the fetal heart. Ultrasound Obstet Gynecol 2017;50:476-491.

59. Goodnight W, Chescheir N. Keepsake prenatal ultrasound: pros and cons of non-medically indicated imaging. N C Med J 2014;75:138-139.
60. Abramowicz J, Brezinka C, Salvesen K, ter Haar G; Bioeffects and Safety Committee; Board of the International Society of Ultrasound in Obstetrics and Gynecology (ISUOG). ISUOG Statement on the non-medical use of ultrasound, 2009. Ultrasound Obstet Gynecol 2009;33:617.
61. Sheiner E, Shoham-Vardi I, Hussey MJ, Pombar X, Strassner HT, Freeman J, et al. First-trimester sonography: is the fetus exposed to high levels of acoustic energy? J Clin Ultrasound 2007;35:245-249.
62. Sheiner E, Freeman J, Abramowicz JS. Acoustic output as measured by mechanical and thermal indices during routine obstetric ultrasound examinations. J Ultrasound Med 2005;24:1665-1670.
63. Sheiner E, Abramowicz JS. Clinical end users worldwide show poor knowledge regarding safety issues of ultrasound during pregnancy. J Ultrasound Med 2008;27:499-501.
64. Abramovicz JS. Ultrasound in the first trimester and earlier: how to keep it safe. In: Abramowicz JS, ed. First-trimester ultrasound. Cham: Springer International Publishing, 2016;1-19.
65. Lees C, Abramowicz JS, Brezinka C, Salvesen K, ter Haar G, Marsal K, et al. Ultrasound from conception to 10+0 weeks gestation. Scientific Impact Paper No. 49. London: Royal College of Obstetricians and Gynaecologists, 2015.
66. Salvesen K, Lees C, Abramowicz J, Brezinka C, Ter Haar G, Marsal K, et al. ISUOG statement on the safe use of Doppler in the 11 to 13 +6-week fetal ultrasound examination. Ultrasound Obstet Gynecol 2011;37:628.
67. Nelson TR, Fowlkes JB, Abramowicz JS, Church CC. Ultrasound biosafety considerations for the practicing sonographer and sonologist. J Ultrasound Med 2009;28:139-150.
68. Goncalves LF, Espinoza J, Kusanovic JP, Lee W, Nien JK, Santolaya-Forgas J, et al. Applications of 2-dimensional matrix array for 3- and 4-dimensional examination of the fetus: a pictorial essay. J Ultrasound Med 2006;25:745-755.
69. Al-Rammah TY, Aloufi AS, Algaeed SK, Alogail NS. The prevalence of work-related musculoskeletal disorders among sonographers. Work 2017;57:211-219.
70. Pike I, Russo A, Berkowitz J, Baker J, Lessoway VA. The prevalence of musculoskeletal disorders among diagnostic medical sonographers. J Diagn Med Sonogr 1997;13:219-227.
71. Barros-Gomes S, Orme N, Nhola LF, Scott C, Helfinstine K, Pislaru SV, et al. Characteristics and consequences of work-related musculoskeletal pain among cardiac sonographers compared with peer employees: a multisite cross-sectional study. J Am Soc Echocardiogr 2019;32:1138-1146.
72. Coffin CT. The continuous improvement process and ergonomics in ultrasound department. Radiol Manage 2013;35:22-25.
73. Ziskin MC, Bonakdarpour A, Weinstein DP, Lynch PR. Contrast agents for diagnostic ultrasound. Invest Radiol 1972;7:500-505.
74. Bruce M, Averkiou M, Tiemann K, Lohmaier S, Powers J, Beach K. Vascular flow and perfusion imaging with ultrasound contrast agents. Ultrasound Med Biol 2004;30:735-743.
75. Abramowicz JS. Ultrasonographic contrast media: has the time come in obstetrics and gynecology? J Ultrasound Med 2005;24:517-531.
76. Abramowicz JS, Miller RK. Ultrasonographic investigations of flow patterns in the perfused human placenta. Am J Obstet Gynecol 2001;184:518-519.
77. Orden MR, Gudmundsson S, Helin HL, Kirkinen P. Intravascular contrast agent in the ultrasonography of ectopic pregnancy. Ultrasound Obstet Gynecol 1999;14:348-352.
78. Kirkinen P, Helin-Martikainen HL, Vanninen R, Partanen K. Placenta accreta: imaging by gray-scale and contrast-enhanced color Doppler sonography and magnetic resonance imaging. J Clin Ultrasound 1998;26:90-94.
79. Denbow ML, Welsh AW, Taylor MJ, Blomley MJ, Cosgrove DO, Fisk NM. Twin fetuses: intravascular microbubble US contrast agent administration: early experience. Radiology 2000;214:724-728.
80. Fleischer AC, Lyshchik A, Andreotti RF, Hwang M, Jones HW 3rd, Fishman DA. Advances in sonographic detection of ovarian cancer: depiction of tumor neovascularity with microbubbles. AJR Am J Roentgenol 2010;194:343-348.
81. DeVore GR, Klas B, Satou G, Sklansky M. Quantitative evaluation of fetal right and left ventricular fractional area change using speckle-tracking technology. Ultrasound Obstet Gynecol 2019;53:219-228.
82. Ligtvoet C, Rijsterborgh H, Kappen L, Bom N. Real time ultrasonic imaging with a hand-held scanner. Part I--technical description. Ultrasound Med Biol 1978;4:91-92.
83. Haaris S, Hassan M. Funding analysis for diagnostic ultrasound companies - 2020 edition [Internet]. Cranfield: Signify Research, 2020 [cited 2020 Jun 3]. Available from: https://s3-eu-west-2.amazonaws.com/signifyresearch/app/uploads/2020/02/02102012/Funding-Analysis-for-Diagnostic-Ultrasound-Companies-2020-Edition-004.pdf.
84. Choi WJ, Ha YR, Oh JH, Cho YS, Lee WW, Sohn YD, et al. Clinical guidance for point-of-care ultrasound in the emergency and critical care areas after implementing insurance coverage in Korea. J Korean Med Sci 2020;35:e54.
85. Ben-Baruch Golan Y, Sadeh R, Mizrakli Y, Shafat T, Sagy I, Slutsky T, et al. Early point-of-care ultrasound assessment for medical patients reduces time to appropriate treatment: a pilot randomized controlled trial. Ultrasound Med Biol 2020;46:1908-1915.
86. Moussa M, Stausmire JM. Do emergency physicians rely on point-of-care ultrasound for clinical decision making without additional confirmatory testing? J Clin Ultrasound 2018;46:437-441.
87. Miller DL, Abo A, Abramowicz JS, Bigelow TA, Dalecki D, Dickman E, et al. Diagnostic ultrasound safety review for point-of-care

ultrasound practitioners. J Ultrasound Med 2020;39:1069-1084.
88. Vinayak S, Sande J, Nisenbaum H, Nolsoe CP. Training midwives to perform basic obstetric point-of-care ultrasound in rural areas using a tablet platform and mobile phone transmission technology-A WFUMB COE Project. Ultrasound Med Biol 2017;43:2125-2132.
89. Feilchenfeld Z, Dornan T, Whitehead C, Kuper A. Ultrasound in undergraduate medical education: a systematic and critical review. Med Educ 2017;51:366-378.
90. Dietrich CF, Hoffmann B, Abramowicz J, Badea R, Braden B, Cantisani V, et al. Medical student ultrasound education: a WFUMB position paper, Part I. Ultrasound Med Biol 2019;45:271-281.
91. Chalouhi GE, Bernardi V, Ville Y. Ultrasound simulators in obstetrics and gynecology: state of the art. Ultrasound Obstet Gynecol 2015;46:255-263.
92. Staboulidou I, Wustemann M, Vaske B, Elsasser M, Hillemanns P, Scharf A. Quality assured ultrasound simulator training for the detection of fetal malformations. Acta Obstet Gynecol Scand 2010;89:350-354.
93. Abuhamad A, Minton KK, Benson CB, Chudleigh T, Crites L, Doubilet PM, et al. Obstetric and gynecologic ultrasound curriculum and competency assessment in residency training programs: consensus report. Am J Obstet Gynecol 2018;218:29-67.
94. Sigrist RMS, Liau J, Kaffas AE, Chammas MC, Willmann JK. Ultrasound elastography: review of techniques and clinical applications. Theranostics 2017;7:1303-1329.
95. Garra BS. Elastography: history, principles, and technique comparison. Abdom Imaging 2015;40:680-697.
96. Seol HJ, Sung JH, Seong WJ, Kim HM, Park HS, Kwon H, et al. Standardization of measurement of cervical elastography, its reproducibility, and analysis of baseline clinical factors affecting elastographic parameters. Obstet Gynecol Sci 2020;63:42-54.
97. Park HS, Kwon H, Kwak DW, Kim MY, Seol HJ, Hong JS, et al. Addition of cervical elastography may increase preterm delivery prediction performance in pregnant women with short cervix: a prospective study. J Korean Med Sci 2019;34:e68.
98. Hasegawa T, Kuji N, Notake F, Tsukamoto T, Sasaki T, Shimizu M, et al. Ultrasound elastography can detect placental tissue abnormalities. Radiol Oncol 2018;52:129-135.
99. Bayramoglu Tepe N, Gelebek Yilmaz F, Bozdag Z, Ugur MG. Subgroup analysis of accreta, increta and percreta cases using acoustic radiation force impulse elastography. J Obstet Gynaecol Res 2020;46:699-706.
100. Britton N, Miller MA, Safadi S, Siegel A, Levine AR, McCurdy MT. Tele-ultrasound in resource-limited settings: a systematic review. Front Public Health 2019;7:244.
101. Wootton R, Dornan J, Fisk NM, Harper A, Barry-Kinsella C, Kyle P, et al. The effect of transmission bandwidth on diagnostic accuracy in remote fetal ultrasound scanning. J Telemed Telecare 1997;3:209-214.
102. Ferreira AC, Araujo Junior E, Martins WP, Jordao JF, Oliani AH, Meagher SE, et al. Trans-Pacific tele-ultrasound image transmission of fetal central nervous system structures. J Matern Fetal Neonatal Med 2015;28:1706-1710.
103. Whittington JR, Magann EF. Telemedicine in high-risk obstetrics. Obstet Gynecol Clin North Am 2020;47:249-257.
104. Bidmead E, Lie M, Marshall A, Robson S, Smith VJ. Service user and staff acceptance of fetal ultrasound telemedicine. Digit Health 2020;6:2055207620925929.
105. Maurice P, Dhombres F, Blondiaux E, Friszer S, Guilbaud L, Lelong N, et al. Towards ontology-based decision support systems for complex ultrasound diagnosis in obstetrics and gynecology. J Gynecol Obstet Hum Reprod 2017;46:423-429.
106. Kim HP, Lee SM, Kwon JY, Park Y, Kim KC, Seo JK. Automatic evaluation of fetal head biometry from ultrasound images using machine learning. Physiol Meas 2019;40:065009.
107. Li J, Wang Y, Lei B, Cheng JZ, Qin J, Wang T, et al. Automatic fetal head circumference measurement in ultrasound using random forest and fast ellipse fitting. IEEE J Biomed Health Inform 2018;22:215-223.
108. Rizzo G, Aiello E, Pietrolucci ME, Arduini D. The feasibility of using 5D CNS software in obtaining standard fetal head measurements from volumes acquired by three-dimensional ultrasonography: comparison with two-dimensional ultrasound. J Matern Fetal Neonatal Med 2016;29:2217-2222.
109. Espinoza J, Good S, Russell E, Lee W. Does the use of automated fetal biometry improve clinical work flow efficiency? J Ultrasound Med 2013;32:847-850.
110. Yeo L, Luewan S, Romero R. Fetal Intelligent Navigation Echocardiography (FINE) detects 98% of congenital heart disease. J Ultrasound Med 2018;37:2577-2593.
111. Christensen-Jeffries K, Couture O, Dayton PA, Eldar YC, Hynynen K, Kiessling F, et al. Super-resolution ultrasound imaging. Ultrasound Med Biol 2020;46:865-891.
112. Zhang J, Li N, Dong F, Liang S, Wang D, An J, et al. Ultrasound microvascular imaging based on super-resolution radial fluctuations. J Ultrasound Med 2020;39:1507-1516.
113. Zhang X, Fincke JR, Wynn CM, Johnson MR, Haupt RW, Anthony BW. Full noncontact laser ultrasound: first human data. Light Sci Appl 2019;8:119.